Speakable and unspeakable after John Bell

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Abstract 'Philosophy' was speakable for John Bell but is not for many physicists. The border between philosophy and physics is here illustrated through Brownian motion and Bell experiments. 'Measurement', however, was unspeakable for Bell. His insistence that the physics of quantum measurement should not be confined to the laboratory and that physics is concerned with the big world outside leads us to examples from zoology, meteorology and cosmology.

Philosophy and physics

I first met John and Mary Bell at CERN because of our common interest in the applications of nonlinear dynamics, but late in life I became sufficiently fascinated by quantum philosophy to follow John Bell's seminal contributions to that field, his 'hobby'.

'Philosophy' is an unspeakable word for many physicists, but it was not for John Bell. He turned the question of local reality, or nonlocality, from a philosophical question to one of physics, by proposing an experimental test, the breaking of inequalities between quantities that are measurable in the laboratory.

The boundary between philosophy and physics is not always clear. Take the earlier example of Brownian motion: " Besides, there is a further reason why you should give your mind to these particles that are seen dancing in a sunbeam: their dancing is an actual indication of underlying movements of matter that are hidden from our sight. There you will see many particles under the impact of invisible blows changing their course and driven back upon their tracks, this way and that, in all directions. You must understand that they all derive this restlessness from the atoms. It originates from the atoms, which move of themselves. . . . So the movement mounts up from the atoms and gradually emerges to the level of our senses ..."

If you wanted to explain Brownian motion to a poet in the twenty-first century, you couldn't do much better than this. But it was not written in this century. It was written in Latin verse *by* the poet and Epicurean philosopher Lucretius, before 55BC. [1]

Despite the clarity and accuracy of the description, the poem shows no evidence of physics as we know it since the Renaissance. For Brownian motion, Brown's systematic studies were published in 1828, following earlier observation using microscopes. The comparison of the detailed theory of Einstein and the experiments of Perrin in the early years of the twentieth century finally established for almost all physicists the reality of atoms.

Physics has many sides, theoretical and experimental, and one important part of it is asking the right questions. Ancient philosophers like Lucretius did that, and modern physicist-philosophers like Einstein, Bell and Shimony have done it too. They have survived on dangerous ground, and built a bridge between unspeakable philosophy and speakable physics.

In physics we are required to put the answers to these questions to the test, particularly experimental test, and here there is a parting of the ways. Lucretius could not distinguish the atomic hypothesis from a continuum hypothesis, or any other. Lucretius's was a philosopher's poem. There was keen observation, but to our knowledge it was not systematic, and there was no attempt to vary the

conditions. His explanation was plausible, but he could not check the validity of the atomic hypothesis. That did not happen for another 1950 years.

In providing his tests of nonlocality, Bell showed how the implicitly philosophical considerations of Einstein, Podolsky and Rosen [2] might be tested in the laboratory. Like the theoretical physicists who studied Brownian motion, he turned the philosophy into physics.

Black boxes and nonlocality

Einstein [3] and Bell [4] were particularly concerned with the question of nonlocal causality, in which cause and effect are spatially separated in spacetime, so that a signal from cause to effect would have to go faster than the velocity of light.

According to classical special relativity, causality can act forwards in time, but it does not act nonlocally over intervals that are spatially separated. An event can affect a future event, in or on its forward light cone, but not a spatially separated event. Consequently signals cannot be sent faster than light.

But apparently, according to quantum theory, classical events that are linked by quantum systems are different. For them, there is a sense in which causality might act nonlocally, but without any signalling faster than light. This is Bell's weak nonlocality, which can be formulated in terms of the inputs and outputs of black boxes.

John Bell in 'Against Measurement' [5], discussed the possibility of an exact formulation of some serious part of quantum mechanics: "By 'serious' I mean that some substantial fraction of physics should be covered.. . . I mean too, by 'serious' that 'apparatus' should not be separated out from the rest of the world into black boxes, as if it were not made of atoms and not ruled by quantum mechanics' Nevertheless, it helps to analyse an experiment to test Bell inequalities as a black box containing classical parts and a quantum system.

An electrical engineer's black box consists of a circuit with input and output terminals. He may not know what circuit is inside, but it is assumed here to be classical. If there is no noise in the circuit, then the black box is deterministic. The outputs j then depend on the inputs i through a unique transfer function F, where

$$j = F(i)$$

and by experimenting with different inputs and looking at the outputs, engineers can find F.

In practice the resistors in the circuit produce noise, which we assume to be classical noise. The system is then stochastic. The noisy circuit can be represented by a probability distribution $\Pr(F)$ over the transfer functions F, in which the unknown values of supposedly classical background variables, like the coordinates of thermal electrons, determine the particular F that operates.

A physicist's black box contains an evolving physical system, such as a classical electrical circuit, or an entangled quantum state with classical inputs and outputs. She may not know what physical system is inside, but by experimenting with different inputs and looking at the outputs, she can find out something about it.

A Bell experiment is an example of a black box with classical terminals and an entangled quantum system inside. We suppose that the source of entanglement is inside the black box, not an input. For photon polarization the setting of the orientations of the polarizers is an input, and the detection of the directions of polarization is an output. All the inputs and outputs are classical events.

If we ignore backward causality, special relativity distinguishes between two types of deterministic system, those with local transfer functions F for which the influence of an input on an output goes at no more than the velocity of light, and those with nonlocal transfer functions, for which the influences can act over spacelike intervals. It is possible to determine whether the transfer function of a system is local or not by experimenting with different values of the inputs, and observing the outputs. There is no need to look inside the black box. All classical systems have local transfer functions, as required by special relativity.

When classical or quantum systems are stochastic, and the inputs are given, the probabilities of the outputs can be obtained from a probability distribution $\Pr(F)$. The stochastic systems are of three main types, with different locality properties.

In the first type only local F contribute. It is therefore not possible to send signals faster than the velocity of light. For the second type, which may soon be seen, transition probabilities can only be obtained from $\Pr(F)$ in which at least one nonlocal transfer function has nonzero probability, so there is an element of nonlocality. But nevertheless it is not possible to send signals faster than the velocity of light. The system is then weakly nonlocal, or nonlocal in the sense of Bell. The *definition* of weak nonlocality needs no quantum theory. For the third type, which we never expect to see, it is possible to send signals faster than the velocity of light.

The stochasticity of classical systems comes from background variables that are not included in the system, but for quantum systems it does not come from any background variables that we can see, so either they are assumed not to exist, as in the Copenhagen interpretation, or they are called hidden variables.

In a Bell experiment in which the entangled quantum system is sufficiently close to a pure state, and the measurements sufficiently good, the black box is weakly nonlocal in the sense of Bell. An experimenter who has never seen the apparatus before can then tell by experimenting with the inputs and outputs, and without looking inside, that the black box contains a quantum system. This property of black boxes containing quantum systems comes from weak nonlocality.

So these black boxes tell us something about the world: there are correlations between classical events that can only be produced by quantum links. These correlations are important in their own right. They are weakly nonlocal. They also show that the properties of our world cannot be explained using local hidden variables, but that is not their main significance.

So weak nonlocality is important for all physicists, whether they are interested in hidden variable theories or not. Weak nonlocality is unique in modern physics: classical dynamics, quantum dynamics and classical general relativity are all local. Nonlocality only occurs in some of those processes for which quantum states influence classical events. Laboratory quantum measurement is such a process, but it is not the only one.

Today only some ideal experiments involving quantum measurement are nonlocal in any sense, though there may soon be real experiments.

The nature of Bell experiments

There is a profound distinction between experiments to test weak nonlocality by the violation of Bell inequalities and most other experiments with quantum systems.

Consider for example an experiment to determine the spectrum of an atom, or a differential cross section for the scattering of an electron by a molecule, or an experiment to determine the band gaps of a solid, or to find a new particle. The aim of all these experiments is to determine the properties of quantum systems. The classical apparatus used to prepare the system and to make the necessary measurements is essential, but secondary to obtaining these properties.

In Bell experiments the converse is true. The aim is to test for violation of the inequalities, which are derived from the (statistical) properties of classical events, such as the setting of the apparatus, which is a classical input, or the detection of a particle by an electron avalanche, which is a classical output. The probabilities of the outputs, given the inputs, are what appear in the Bell inequalities, and it is the location of these events in spacetime that determine the locality or nonlocality.

These classical events are connected by an ancillary quantum system, whose function is to produce their unusual statistical properties. The quantum properties, like the entanglement of particles, or the polarization of photons, or the spins of atoms, are essential, but secondary. The primary result is the violation of an inequality. The apparatus as well as the quantum system is essentially involved.

This distinction has implications for the analysis of Bell experiments. Real Bell experiments are designed to approximate ideal experiments. But the classical

events in a real experiment are usually different from those in the ideal experiment which it simulates. There are generally more types of possible output. For example, in an ideal experiment, it is usually assumed that the detectors detect every particle, but in real experiments they don't.

It follows that the inequalities of the ideal experiment do not always apply directly to the real experiment, and further assumptions are needed to demonstrate weak nonlocality.

There are two ways to tackle this problem.

One is to perform those special experiments for which the ideal and the real are the same. In these the detectors do not distinguish between some of the particle quantum states and a failure to detect a particle. Experiments to test the Clauser-Horne-Shimony-Holt inequality is of this type, so this inequality has been widely used.

Another way is to recognize that every real experiment that simulates an ideal Bell experiment has its own critical inequalities, that apply directly to the probabilities for all the outputs of the real experiment. These can be derived from the condition that all the $\Pr(F)$ are local. The larger the number of detectors, the larger the number of inequalities, and a computer program may be needed to obtain them.

If any one of these inequalities is violated, weak nonlocality has been demonstrated, and no further assumptions are needed.

Measurement

was an unspeakable word for John Bell:

John Bell: Against 'measurement' *Physics World* 33-40 Aug 1990, p34: " When I say that the word 'measurement' is worse than the others ... I do have in mind its use in the fundamental interpretive rules of quantum mechanics. ... " The first charge against 'measurement', in the fundamental axioms of quantum mechanics, is that it anchors there the shifty split of the world into 'system' and 'apparatus'. " I will not be discussing this charge. It does not apply to explicit dynamical models of physical processes of which quantum measurement is an example, and these are discussed by Gian-Carlo Ghirardi at this meeting.

" A second charge is that the word comes loaded with with meaning from everyday life, meaning which is entirely inappropriate in the quantum context. When it is said that something is 'measured' it is difficult not to think of the result as referring to some preexisting property of the object in question. This is to disregard Bohr's insistence that in quantum phenomena the apparatus as well as the system is essentially involved. "

This charge was avoided above by treating the quantum system and classical apparatus together as a single system.

“ In the beginning natural philosophers tried to understand the world around them.... Experimental science was born. But experiment is a tool. The aim remains: to understand the world. To restrict quantum mechanics to be exclusively about piddling laboratory operations is to betray the great enterprise. A serious formulation [of quantum mechanics] will not exclude the big world outside the laboratory. ”

I will discuss this third charge now.

The big world

Traditionally quantum measurements take place in the laboratory, but the laboratory is only part of our universe, and all such measurements start out as imitations of natural phenomena.

Cloud chambers were based on the physics of clouds, which are natural detectors of charged particles. Spark chambers imitate lightning. We can generalize *quantum measurement* to mean any process whereby the state of a quantum system influences the value of a classical variable. This definition then applies to the big world.

Laboratory quantum measurements include particle states producing the droplets in cloud chambers, bubbles in bubble chambers and sparks in spark chambers. They include photon states producing silver grains in photographic emulsions, and also electron avalanches in solid state detectors and photomultipliers.

Other quantum measurements include photon states sending impulses through the optic nerves of owls, the states of cosmic rays that produced small but very long-lived dislocations in mineral crystals in the Jurassic era, and the quantum fluctuations that are believed to have caused today’s anisotropies in the universal background radiation and in galactic clusters.

This takeover of the physics of laboratory quantum measurement into the world outside the laboratory is here generalized, and one of the questions we have to ask is how far this generalization can go.

Equilibrium gases

Laboratory systems used for quantum measurement are very complicated physical systems, even stripped down to their bare essentials. They involve amplification in one form or another, and so do the natural systems that they imitate.

A gas in equilibrium is much simpler, yet generalized quantum measurement takes place there also. The reason is that the motion of the molecules in the

gas is chaotic, and small changes now result in large changes later. In particular changes at the quantum level now produce significant classical fluctuations in the density later. However, unlike earlier examples, we can't use the classical density fluctuations to learn anything specific about these earlier quantum states, because the chaos causes mixing, which effectively obscures the signal.

In the nineteenth century, Rayleigh recognized that these classical density fluctuations would scatter light, and that the scattering was strongly dependent on the wavelength of the light. The result is the blue of the sky.

The growth of droplets of water around the charged particles produced by cosmic rays in the atmosphere is a quantum measurement. So are the density fluctuations in the atmosphere that cause the sky to be blue where there are no clouds. So if you ever look at the sky, as every physicist sometimes should, whether it is clear or overcast, you are seeing one example or another of quantum measurement.

Theoretical cosmology makes a prediction

According to the cosmologists there occurs in the early universe a generalized quantum measurement. Quantum fluctuations produce fluctuations in classical variables and these are then rapidly stretched from subatomic scales to the size of galaxies or even larger. So according to this theory, the inhomogeneities in the universe, such as galactic clusters, galaxies, and the fluctuations in the background radiation are all due to quantum measurement in the early universe. Somewhat later, physicists meeting in Vienna were also produced by fluctuations from the same process of quantum measurement.

Recently there have been several detailed observations of the inhomogeneities in the universal background radiation, for example those of the 'Boomerang' project [6]. The intensity of the fluctuations were plotted as a function of the order of the spherical harmonics, as illustrated in the figure. There is a pronounced peak.

The observations are compared with theory, represented by the continuous curve, and based on the assumption of a flat universe. The theory shows the same peak, and a number of smaller peaks which are not (yet) seen. By the standards of cosmology, the agreement between theory and observation is excellent, providing evidence for quantum measurement in the early universe.

Conclusions

One of John Bell's major objections to quantum 'measurement' might be overcome by generalizing the definition to include processes in the big world. With this extended definition, quantum measurement is a universal property of physical systems. It is all around us, and we would not be here without it.

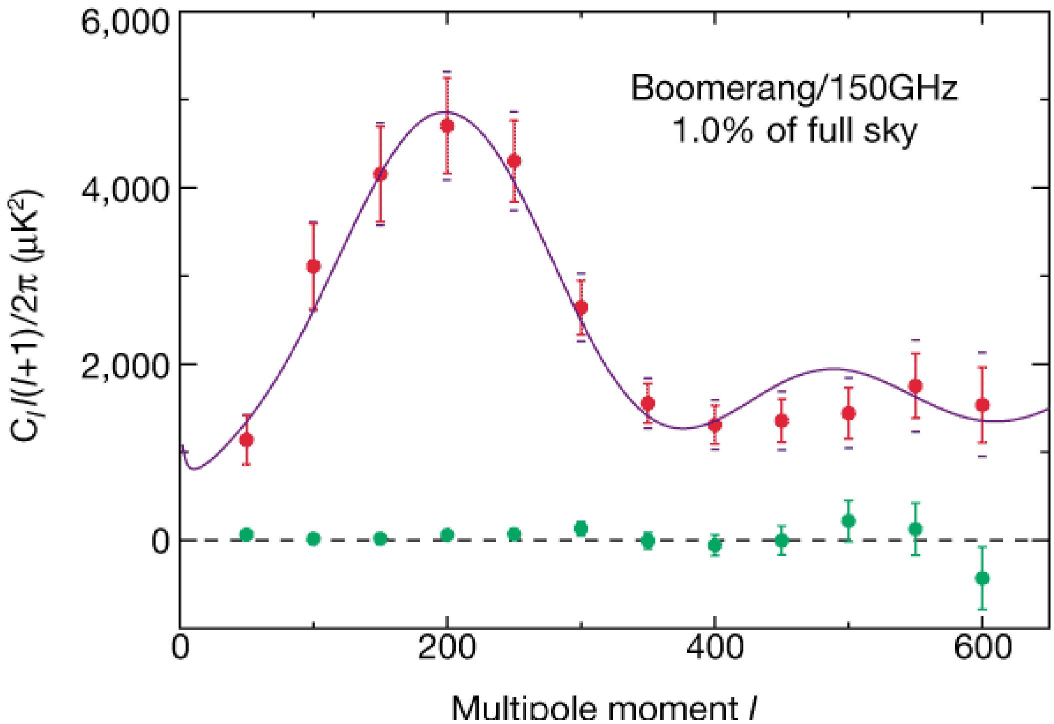

Figure 1: Theory (continuous line) and experiment for inhomogeneities in the universal background radiation

Consequently the dynamics of quantum measurement has universal significance. So have its properties, like the weak nonlocality of John Bell.

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